Dark Energy Task Force White Paper:
Baryon Oscillations with the "One Thousand Points of Light Spectrograph"

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Introduction

There are a limited number of proven techniques for measuring the effects of dark energy on the expansion history of the Universe. Working our way from the nearby to the distant Universe: gravitational lensing of galaxies is sensitive to the effects of dark energy at $z < 1$, supernovae are sensitive at $0 < z < 2$, baryon acoustic oscillations (BAO) have potential at $0 < z < 3$. and the microwave background adds the most distant constraint at $z = 1100$. The angular diameter distance technique of baryon oscillations has only just been proven with the publication of Eisenstein *et al.* (2005).

The full potential of supernovae and weak lensing require space missions. The baryon oscillation experiment is unique in these methods in that one can reach the cosmic variance limit from the ground in the redshift intervals $0 < z < 1.2$ and $z > 2.2$.

Our intention is to measure the baryon oscillations from the ground with existing wide-field correctors on existing telescopes. A simple, scalable design for a 1000-fiber spectrograph will be prototyped in the next two years at Lawrence Berkeley Lab. Our initial goal is to survey 1 million galaxies at $0.7 < z < 1.2$ on a 4-m class telescope, followed by 1 million galaxies at $2.3 < z < 3$ on a 10-m class telescope.

Baryon Oscillations: The Method

The dark energy measurment that has only just proven its usefulness is baryon oscillations. In the early Universe, when baryons were an ionized plasma, sound waves travelled at near the speed of light. The plasma age ends abruptly and freezes in sound waves as shells of material that today span $100h^{-1}$ Mpc. These sound waves can be used as standard rulers in much the same way that supernovae have been used as standard candles: we measure the apparent size of these features on the sky. Additionally, this scale can be compared to the acoustic peaks in the microwave background, thus tying these standard rulers to $z = 1089$. The experiment is conceptually very simple: we need measure only positions and redshifts of galaxies, without the complicated calibrations or corrections used in supernova work.

The first results from this method was recently published by Eisenstein *et al.* (2005). In that study, a volume of $0.7h^{-3}$ Gpc^3 was sampled (3800 square degrees at $0.15 < z < 0.45$) with luminous red galaxies from the Sloan Digital Sky Survey (SDSS). Redshifts were obtained for the most luminous 50,000 galaxies with the same telescope, and the 3-dimensional correlation function was measured. The acoustic peak is evident at the $\sim 3.4\sigma$ level (Figure 1).

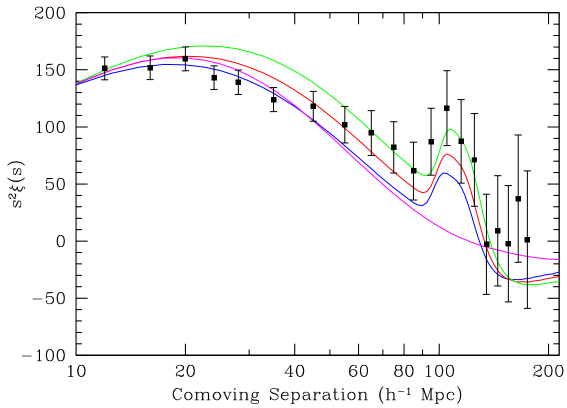

Figure 1: The large-scale correlation function of the SDSS luminous red galaxy (LRG) sample (Eisenstein *et al.* 2005). The bump at $100h^{-1}$ Mpc is statistically significant and is an excellent match to the predicted shape and location of the imprint of the acoustic oscillations. The models are $\Omega_m h^2 = 0.12$ (top), 0.13 (middle) and 0.14 (bottom with peak). The bottom line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak.

Baryon Oscillations: "One Thousand Points of Light" Spectrograph

The BAO experiment relies upon measuring the redshifts to large numbers of objects in large volumes. The statistical errors on the power spectrum can be approximated as

$$\frac{\sigma_P}{P} = 2\pi\sqrt{\frac{1}{Vk^2\Delta k}}\left(\frac{1+nP}{nP}\right) \tag{1}$$

where V is the volume of the survey, n is the number density, and P is the power. A plot of the expected errors in recovered cosmological parameters for different choices of V and n is shown in Figure 2. It can be seen that the SDSS LRG result is shot-noise limited using only 50,000 galaxies, meaning that the white noise power from Poisson sampling of the density field exceeds the true clustering power.

Observationally, the feasible approach is to measure objects at the "tip of the luminosity function", as was done with the LRGs. With ground-based telescopes, there are two redshift ranges at which one can easily perform the baryon oscillation experiment: $z \sim 1$ and $z \sim 3$. At $z < 1.2$, one can measure the $4000-\AA$ break in galaxy spectra. At $z > 2.2$, one can measure the Lyman-alpha break, which is redshifted into the optical. It should be noted that the redshift interval $1.2 < z < 2.2$ would be very difficult to explore from ground-based optical telescopes.

The "trade studies" of number of objects and volume of the Universe (sky

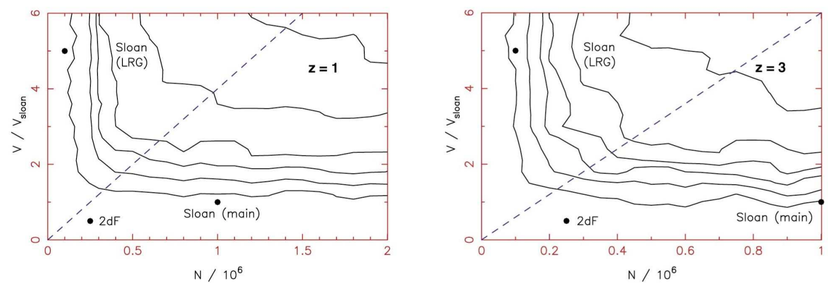

Figure 2: Fractional accuracy $\delta k_A/k_A$ with which the wavescale of the baryonic oscillations in k-space can be measured at redshift $z \sim 1$, as a function of the number of galaxies N and the survey volume V (as a fraction of the SDSS volume $V_{\rm Sloan} = 2 \times 10^8 h^{-3} Mpc^3$). Contours are shown corresponding to (beginning in the bottom left-hand corner) $\delta k_A/k_A$=10%, 5%, 3% and 2%. The positions of the 2dF and SDSS survey are marked on the plot for comparison. The dashed line corresponds to a surface density ~ 2400 galaxies deg^{-2} in this case. (From Blake & Glazebrook 2003).

coverage) have been extensively studies by many authors. In order to attain errors of $\sim 2\%$ in $H(z)$ and D_A, one requires redshifts to 10^6 galaxies in an area of ~ 2000 square degrees (at $z \sim 1$) and in ~ 200 square degrees (at $z \sim 3$) in order to map a sufficient volume of the Universe (see Figure 3). Interpreting these constraints under the paradigm of an w_0-w_a parameterization is shown in Figure 4.

Instruments *do* exist that could deliver BAO spectroscopic redshifts to $z = 0.7$. Both the SDSS spectrograph (on a 2.5-m telescope) and the 2dF spectrograph (on a 4-m telescope at a lesser site) can measure redshifts to the most luminous red galaxies to z=0.7 in 1 hour. However, neither has the red sensitivity to efficiently explore beyond $z = 0.7$. And neither has the blue sensitivity (nor aperture) to explore Lyman-break galaxies at $z > 2.2$.

In order to perform the BAO experiment on existing telescopes in finite time, one is driven to designs that can observe 1000 objects at a time. With ~ 1 hour integrations on 1000 fields, this still requires ~ 150 nights of dark time on each telescope. Our proposal is to build a 1000-fiber spectrograph for existing telescopes. The spectograph would have to be sufficiently red-sensitive to measure the $4000 - \mathring{A}$ break for the $z \sim 1$ sample, and sufficiently blue-sensitive to measure the Lyman-alpha break for the $z \sim 3$ sample. Our baseline plan is to split the experiment into these two redshift regimes, where the former is done on 4-m class telescope with a 1-degree FOV, and the latter on a 10-meter telescope with a 1/6-degree FOV.

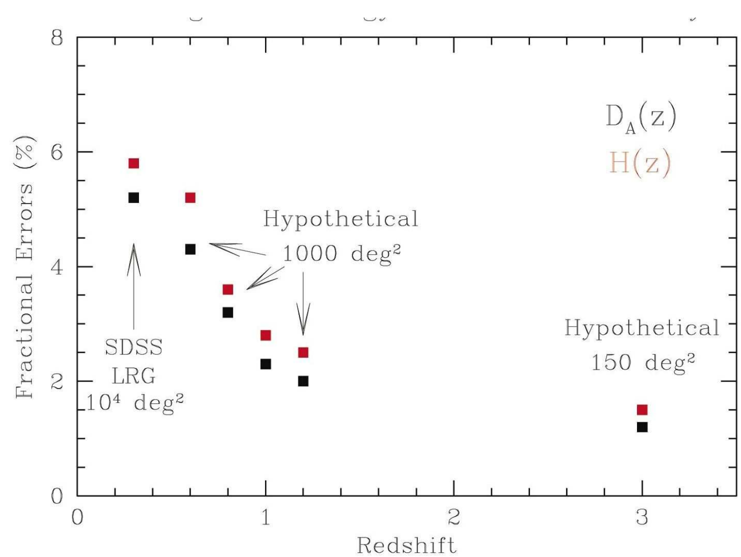

Figure 3: Fractional errors on the Hubble parameter and angular diameter distance for a spectroscopic BAO survey of 1 million galaxies in 1000 deg^2 at $0.5 < z < 1.3$, and 500,000 galaxies in 150 deg^2 at $z \sim 3$. (From the KAOS Purple Book.)

Error Budget

A uniform target selection, and high-quality spectroscopic follow-up effectively removes observational errors.

This reduces the errors to such that the *theoretical* errors dominate. The shape of the BAO signature in the correlation function (or equivalently, $P(k)$) is fairly-well understood from linear theory. However, at the level of precision we hope to achieve, redshift-space distortions, the nonlinear growth of LSS, and scale-dependence of galaxy biasing is expected to begin to impact upon the results. This clearly needs more work, in particular with numerical simulations larger than the volumes of the proposed BAO experiments.

Risks and Strengths

This project *would be* higher-risk if photometrically-determined redshifts (photo-z's) were proposed rather than spectroscopic redshifts. Using photo-z's demands extremely good understanding of the redshift calibrations, as well as the full *distribution* and the *errors in that distribution*. There is also the risk that photo-z's may not be as well-behaved at $z > 0.5$ as they are at lower redshifts. This risk factor is one of the reasons that we have opted for pursuing the next-generation BAO experiment with spectroscopic redshifts.

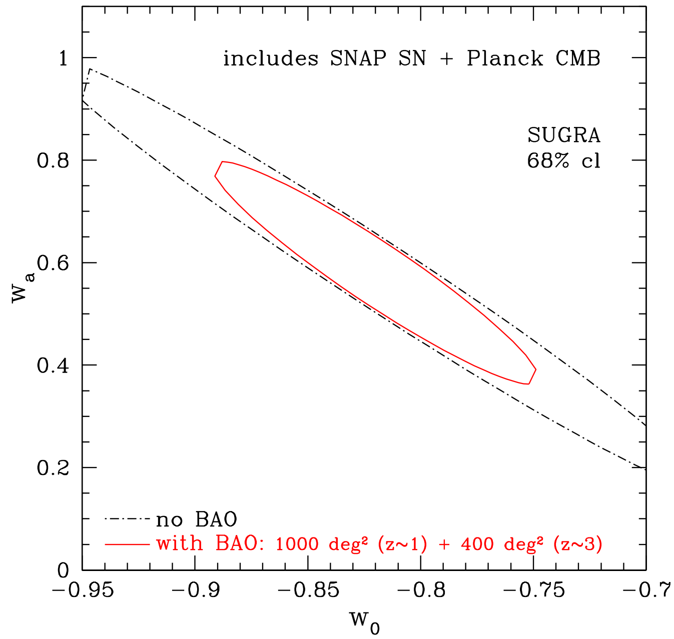

Figure 4: Cosmological parameter constraints at the 68% confidence level on the dark energy equation of state today, w_0, and its variation, w_a, show that a spectroscopic survey of baryon acoustic oscillations can provide significant complementarity with precise supernova and CMB last scattering distance information. This is especially true when the dark energy remains non-negligible at $z \geq 1$, as in the supergravity inspired SUGRA dark energy case shown here.

For the $z \sim 1$ experiment, the red-response of CCDs would have been a risk factor until now. MIT/Lincoln Labs and LBL have independently developed depleted CCDs that have significantly better response at $\lambda > 8000\AA$ and very little fringing. (Such a device has been fielded on the MARS spectrograph at NOAO.) It is with these devices that we expect to be able to obtain absorption-line redshifts for luminous $z \sim 1$ galaxies (at $i \approx 21$) on 4-m class telescopes. These studies are in progress.

Baryon Oscillations: Precursor Observations

The spectroscopic approach to BAO requires target lists in each of the redshift regimes. Because the requisite space densities are quite low, any “tip of the luminosity function” selection will work. Such selections have the additional benefit that more luminous objects are both biased (increasing the signal), and more easily observed.

At redshifts $z < 0.7$, SDSS has a photometric sample of 1 million galaxies over 5000 deg^2. These are luminous red galaxies (LRGs) selected from *gri*-imaging, and currently being used for a photo-z baryon oscillation study by Padmanabhan *et al.* (in prep).

At distances beyond $z > 0.7$, there are currently no photometric samples of sufficient area and depth. The RCS2 survey on the CFHT telescope is imaging 1000 deg^2 in grz-bands to sufficient depth for a $z \sim 1$ BAO experiment, though the geometry is unsuitable (the largest patch being 72 deg^2). The RCS2 survey could be supplemented with additional observations to make larger, contiguous areas. Note that the first three years of this survey become public in 2006.

If Pan-STARRS were to begin observing in 2006 or 2007, it would be capable of target selection for both $z \sim 1$ and $z \sim 3$ samples. This would require sufficient observing time in $rizY$-bands over 1000 deg^2 for the $z \sim 1$ sample, and in ugr-bands over 200 deg^2 for the $z \sim 3$ sample. We would want these observations to be contiguous. It is our hope that such data could be taken with Pan-STARRS within the priorities of their other projects.

Several other existing or planned instruments would be capable of photometric target selection for a spectroscopic BAO survey. Existing wide-field imagers are the MOSAIC at the Kitt Peak 4-m, MOSAIC at the Cerro Tololo 4-m, IMACS at Magellan and Suprime-Cam at Subaru. Future wide-field imagers are the VLT Survey Telescope (VST) at the VLT site, the Discovery Channel Telescope at Mt. Graham, the Dark Energy Survey (DES) at Cerro Tololo, and LSST.

Facilities

Telescope facilities are available for a spectroscopic BAO program. NOAO is looking for partners with new instruments for its 4-m-class and smaller telescopes, such as the Kitt Peak 4-m. The Lick 3-m is an underutilized telescope with old instruments, and the Keck I is in need of new instruments. Without developing any new wide-field correctors (at high risk and cost), there are 1-degree fields of view on the Lick 3-m and the MMT 6.5-m which would be suitable for the $z \sim 1$ BAO experiment. For the $z \sim 3$ experiment, one could plausibly make use of the 25 arcmin fields of view of the KPNO 4-m, CTIO 4-m, Magellan, Subaru and Keck.

Timeline

We are proceeding at LBL with the pacing items for a wide-field, 1000-fiber spectrograph (or two!). In the next year, we will prototype and test several designs for individually-actuated fiber positioners. In the following year, we will connect these fibers to a deployable instrument that will allow testing various approaches to sky-subtraction.

After these two years, we would be in a position to replicate these components for a 1000-fiber instrument. The only large component would be the mounting structure for the fiber actuators on the focal plane.

Competing Proposals

Competing proposals for measuring baryon oscillations are being developed at other institutions. These are typically much more ambitious and costly (VIRUS spectrograph on HET, KAOS spectrograph on Gemini) that are piggy-backing on general-use instruments with many other capabilities. None are currently funded, and the timescales place them well after 2010. There are also ideas for JDEM that would make the baryon oscillation measurements from space. Our contention is that there is no need for either the more complicated spectrographs (which would still require $\sim$ 1000 fibers), or for space-based missions.

The measurements can be done from the ground in advance of JDEM In so doing, we provide JDEM with results that would help inform the optimal observing strategy for a supernovae and/or weak lensing mission.

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